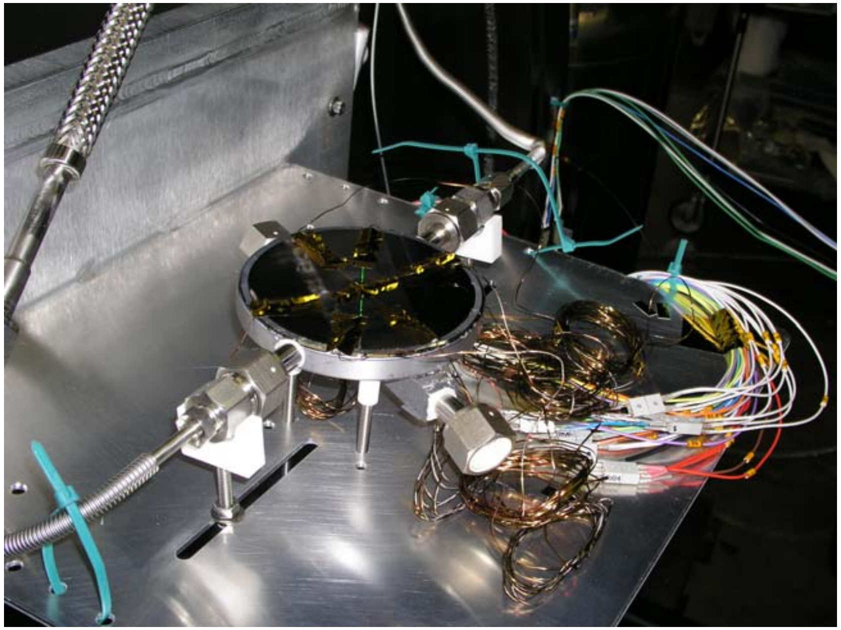
Actively Cooled Silicon Lightweight Mirrors for Far Infrared and Submillimeter Optical Systems
Phase II SBIRContract No, NNM05AA16C
John West and Dr. Phil Stahl NASA MSFC



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Mirror Technology Days
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Outline

- Background
- Why SLMS™ for Cryogenic Optics
- Phase II Project

Background

- Achieving a telescope temperature of 4 Kelvin is one of the key technology development demonstrations that must occur in order to unravel the secrets of the early universe
- ~50% of the luminosity of the universe and 98% of the photons (excluding the cosmic microwave background) occur in the FIR
  - ⇒ That is where the young universe is redshifted
- Development of technology for 10-25 meter diameter optics for 20-800 μm bandwidth, with an areal density <5 kg/m^2, and a surface figure specification of λ/14 at 20 μm required for future FIR/SMM missions
  - ⇒ Premium for wavelengths >100 μm to achieve mirror temperatures lower than 10 K
  - ⇒ Some missions such as TPF-C require extreme figure and finish performance
- TRL 6 must be demonstrated for Cryogenic Optics and Telescopes
- SLMS™ technology development and demonstration effort is directly aligned with the vision of the FIR/SMM community

Why SLMS™ for Cryogenic Optics (1 of 2)

- Super-polishable, low distortion, dimensionally stable silicon skin:
  - ⇒ Avg CTE from 20-310K = 0.95 ± 0.01 ppm/K, 0.25 ppm/K instantaneous @ 20K
  - ⇒ High thermal conductivity: >5000 W/m-K at 25 K
- Silicon foam core is open-celled (up to 95% void space)
  - ⇒ Same CTE as skin, thermal conductivity ~50 W/m-K
  - ⇒ 1st fundamental frequency (120.35 ± 0.175 Hz) and damping (0.0055% ± 0.0043%) are temperature insensitive from 20-300K (20x2x0.5 inch bar measured by JPL – values are geometry dependent)
- *Static and Transient Distortion parameters are incredibly small!*
- SLMS™ engineered construct provides areal density and 1st fundamental frequency that match or exceeds lightweighted beryllium
- *High-stiffness reduces risk for phase matching segments*
- SLMS™ is super-polishable like glass or glass-ceramics
- *Exceptional figure and finish values have been demonstrated*

Why SLMS™ for Cryogenic Optics (2 of 2)

- *SLMS™ can be cooled either Internally or Externally*
- Phase I demonstrated Very Rapid and Uniform cooling for both Internal and External cooling modes with LN2
- Uniform external cooling of skin using Joule-Thompson cooler, or manifold, or cold plate, etc.
- *In situ* heat exchanger for Internal Cooling
  - ⇒ Uniform active cooling by flowing a coolant fluid (e.g. LHe) directly through foam core of mirror
  - ⇒ Foam structure has large surface area, and low flow resistance
  - ⇒ 1 ft^3 of foam has 1500-2000 ft^2 of heat transfer surface area
- Prior testing at NASA MSFC demonstrated minimal print-through (3.7 nm RMS) and figure change ($\lambda/100$ RMS HeNe) for 300 K to 24 K temperature change (radiative)

SLMS™ Transient Distortion Parameter is Orders of Magnitude Better Than Any Other Material

No Cryo-Nulling is Required, No Actuators for Figure Control

High Stiffness Should Minimize Phase Matching Issues

Phase II Project

- Matures Cryogenic Optic Technology to TRL6 at Component Level
  - ⇒ In Line With NASA Technology Development/Demonstration Goals
- Provides Useable Primary Mirror for Future NASA Mission
- Phase II Project Tests 55 cm Diameter SLMS™ Mirror at 4K using External Active Cooling
  - ⇒ Far Infrared Submillimeter Prototype (FISP) Mirror (Deliverable)
  - ⇒ Manifold/Mount for Cooling to 4 K (Deliverable)
  - ⇒ Vacuum-Cryogenic Test to 4 K at NASA MSFC

Requirements Definition Task

Mass Study of SLMS™ 50 cm Mirror

Cesic Cooling Manifold

Mirror/Manifold Assy Thermal Analysis

Overview

- Preliminary Designs to Provide Basis for Discussion with NASA Mission Stakeholders
  - ⇒ GSFC: Ray Boucarut and Chris Schwartz, JPL: Marty Levine
- These are NOT Optimized Designs
- Compared Flat-Back and Meniscus SLMS™ Configurations
- Meniscus Provides Lowest Weight
  - ⇒ More Difficult Polishing and Metrology Mount
  - ⇒ More Difficult Integration
- Flat-Back Moderately Heavier
  - ⇒ Desirable for Polishing and Mounting
  - ⇒ Easier Mount for Manifold and Testing
  - ⇒ More Cost and Schedule Effective
- Assumptions for Analysis:
  - ⇒ 5-meter ROC
  - ⇒ 1.5-meter ROC
  - ⇒ Central Hole Not Included At This Time
  - ⇒ 10% Relative Density Silicon Foam Core
  - ⇒ 0.04 inch thick closeout

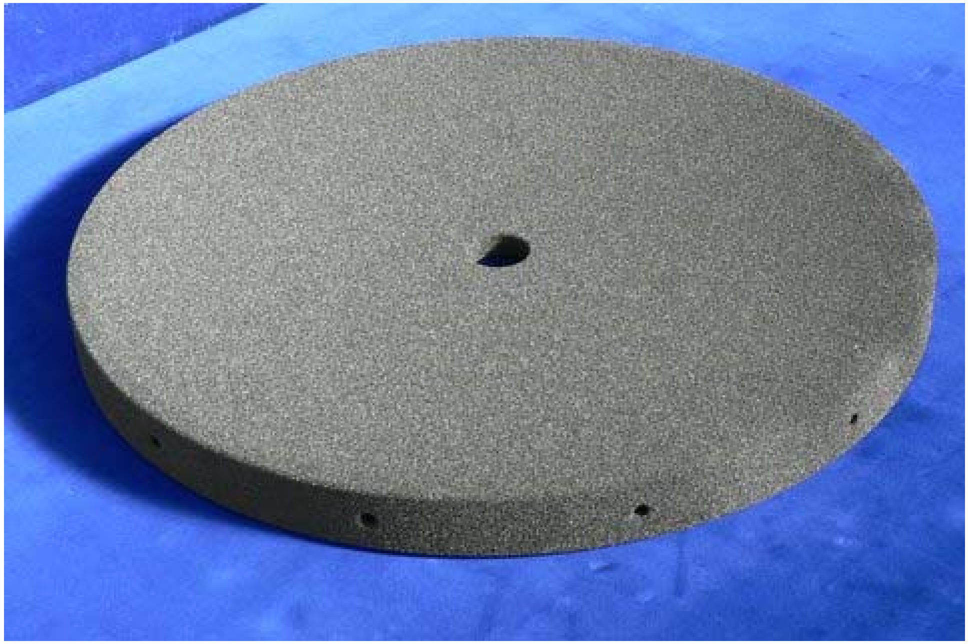
Summary of Mirror Properties

Mass Properties	1.5-m Meniscus	1.5-m Flatback	5.0-m Flatback
Mass (kg)	1.237	1.976	1.450
$Area_{CA}$ (m^2)	0.198	0.198	0.196
Areal Dens. (kg/m^2)	6.247	9.979	7.398

Physical Properties	1.5-m Meniscus	1.5-m Flatback	5.0-m Flatback
ROC (cm)	150	150	500
CA Dia. (cm)	50.0	50.0	50.0
Overall Thick (cm)	1.27	4.10	2.03
Overall Dia. (cm)	55.0	55.0	55.0
Sag (cm)	2.52	2.52	0.76

New Phase II Baseline

- Far Infrared Submillimeter Prototype (FISP) Mirror Suitable for Testing at NASA MSFC and Subsequent ST-9 Mission Telescope
  - ⇒ Optical
    - → CA: 50-cm
    - → ROC: 1500-mm
    - → Kappa: -1.0 (parabola)
  - ⇒ Mechanical
    - → Overall Dia.: 55-cm
    - → Overall thick.: 4.1-cm
    - → Front annulus: 0.7-cm
    - → Flatback
  - ⇒ Material Properties
    - → 1.3-mm Silicon Closeout
    - → 10-12% Silicon foam
  - ⇒ Mass Properties
    - → Mass = 1.976 kg
    - → Areal density = 9.98 kg/m^2

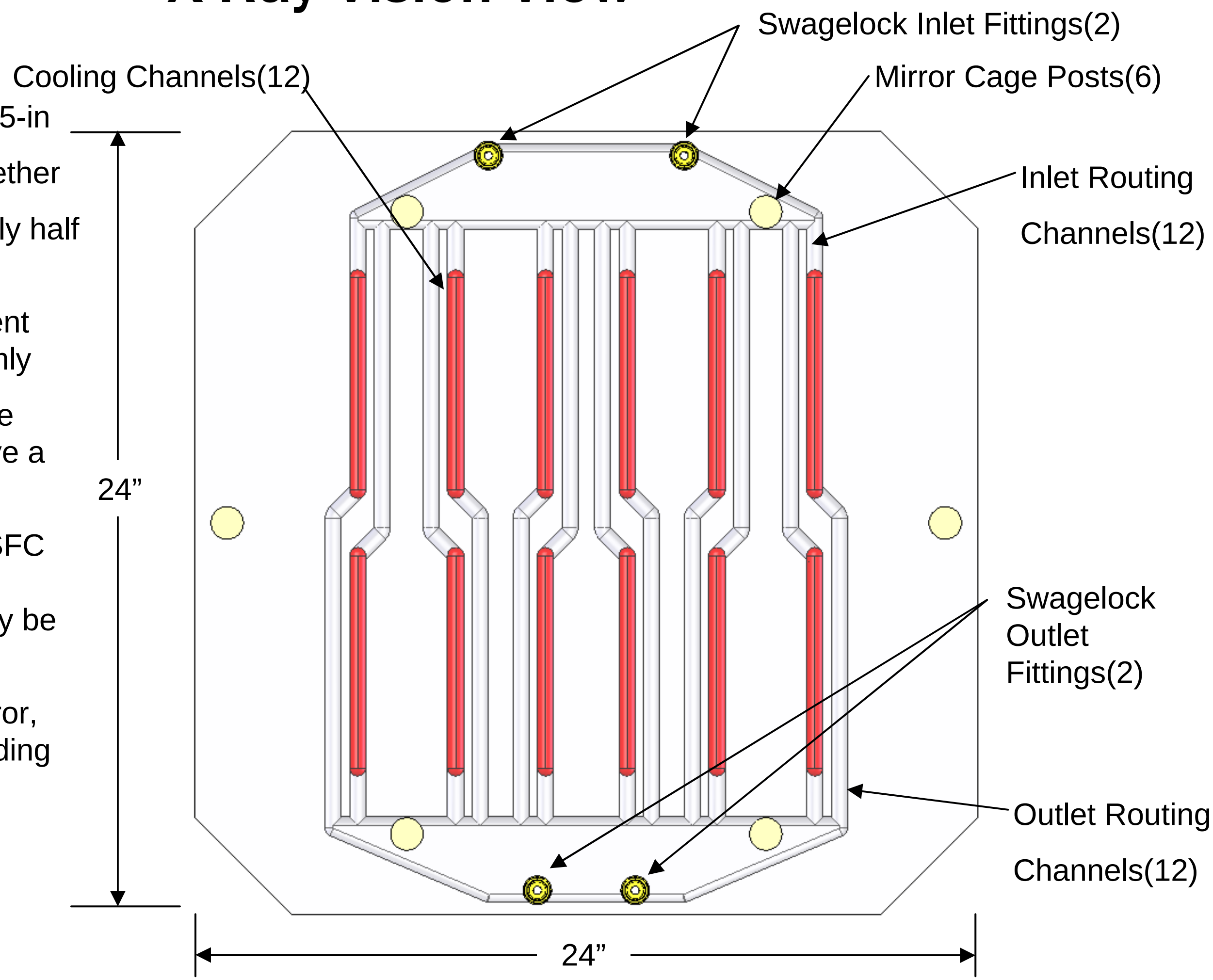


Silicon Foam Core Presently Being Polysilicon Coated

Cesic Cooling Manifold

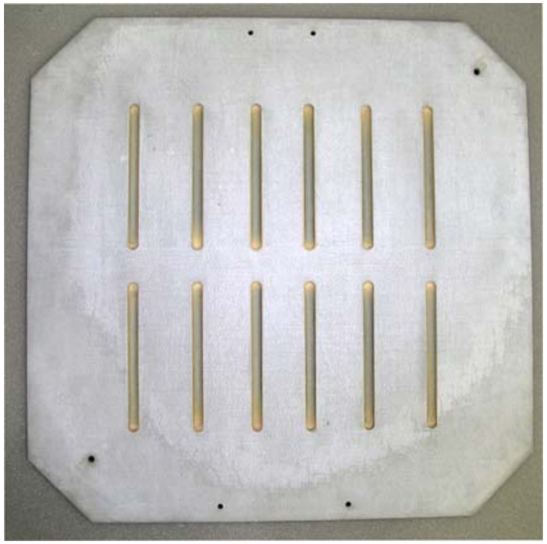
X-Ray Vision View

- Overall Dimensions:24-in x 24-in x 1.5-in
- Upper and lower section bonded together
- 12 cooling channels run approximately half the length of the mirror
  - This disperses the cooling agent across the mirror more uniformly
  - Six cooling channels, the entire length of the mirror, would have a cooler side and a warmer side
- INVAR Swagelock Fittings match MSFC test fixture. Depending on flow requirements, one or both fittings may be used
- Mirror cage Posts do not contact mirror, but will catch it if there is any de-bonding when the fixture is vertical

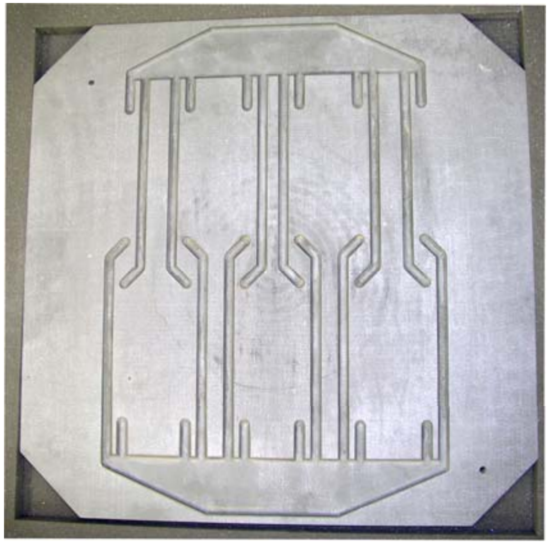


Manifold Components

- Manufactured Upper Manifold Section
  - ⇒ 12 Cooling Channels on under side match routing channels in lower component
    - → 0.5-in x 7-in.
    - → Fully rounded edges minimize possibility of eddies
  - ⇒ INVAR insert counterbores
    - → 6 inserts for Cage Posts
    - → 4 inserts for Swagelock fittings



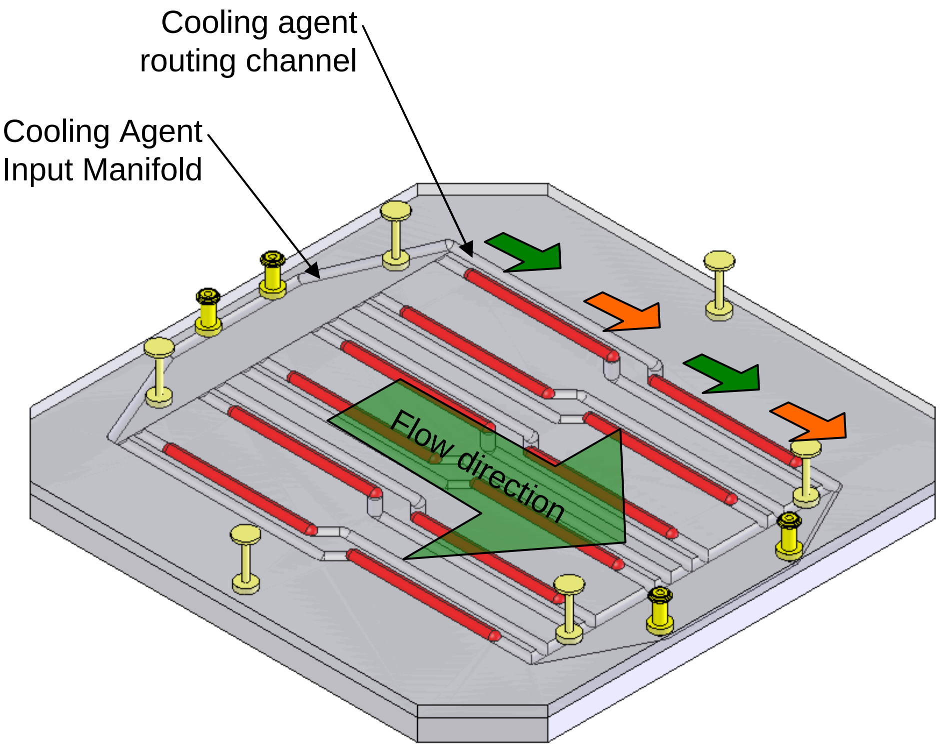
- Manufactured Lower Manifold Section
  - ⇒ Strategic routing distributes fluid evenly throughout the cooling surface
  - ⇒ Fluid passage geometry contains no sharp corners or flow restrictions, thus eliminating eddy current effects and reducing pressure losses
  - ⇒ Continuous cross-sectional area distribution ensures a constant volumetric flow rate throughout the manifolds
  - ⇒ Inlet and Outlet reservoirs



Cooling Scheme

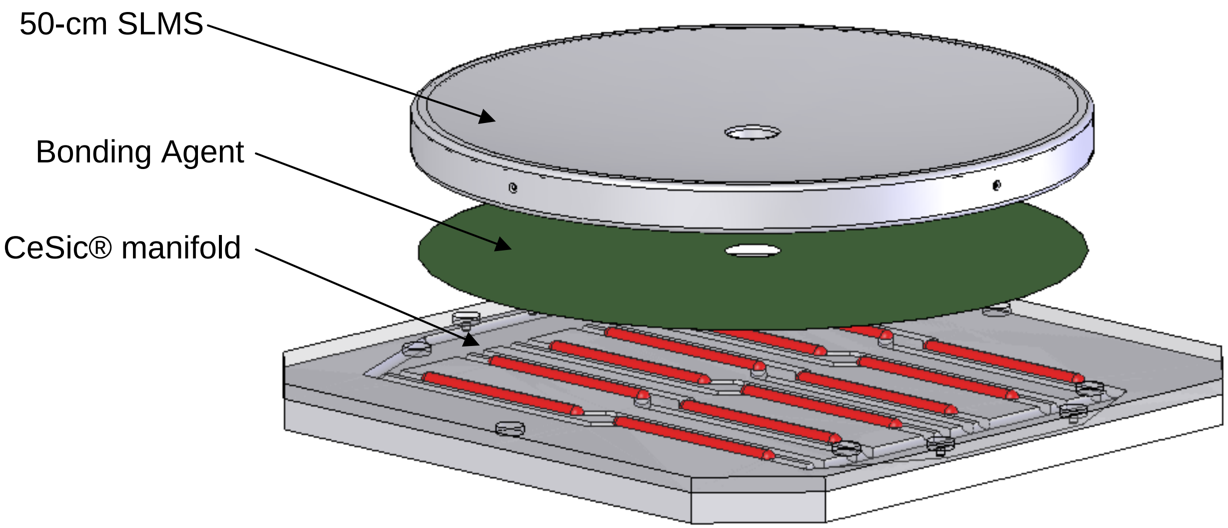
Method Of Operation

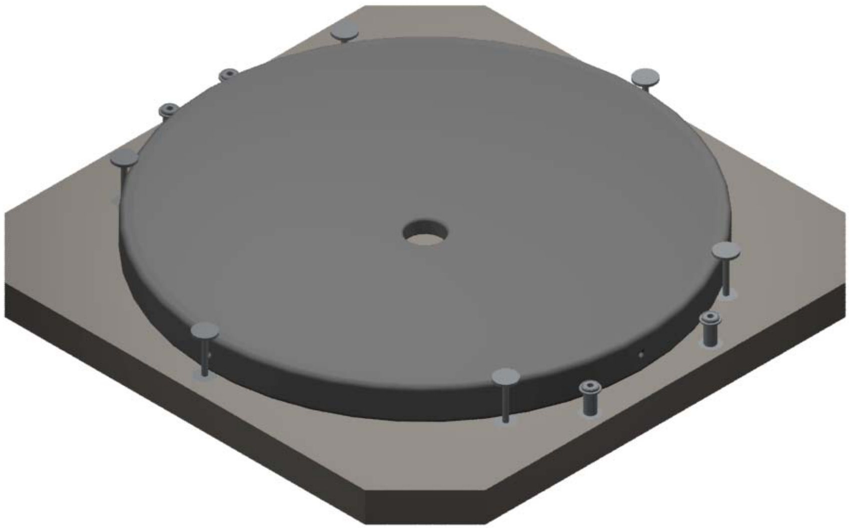
1. Routed pathways in lower manifold section deliver cooling agent uniformly throughout mirror back plate.
2. Ports then surface towards mirror back to route cooling agent near mirror back surface.
3. Cooling agent passes through channels, removing heat from mirror.
4. Cooling agent then returns back down to lower manifold section where it exits the device.



Assembly Model

- 50-cm SLMS™
  - ⇒Optical
    - →CA: 50-cm
    - →ROC: 1500-mm
    - →Kappa: -1.0 (parabola)
  - ⇒Mechanical
    - →Overall Dia.: 55-cm
    - →Overall thick.: 4.1-cm
    - →Front annulus: 0.7-cm
  - ⇒Material Properties
    - →1.3-mm Silicon Closeout
    - →10-12% Silicon foam
- Bonding agent
  - ⇒Approximately .004-in thick bond line continuous over back surface of mirror.
    - →For ease of analysis, this may change.
- Manifold
  - ⇒C/SiC upper and lower halves
    - →Upper half routes cooling agent near mirror
    - →Lower half routes cooling agent to and from test stand





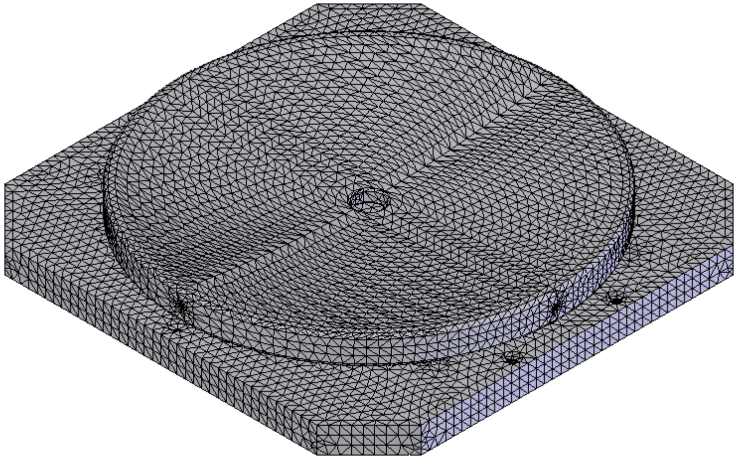
Analysis Description

- Modeled to Approximate/Predict Mirror Surface Changes During Experiment
- Assumption: No Losses due to Radiation, Conduction or Convection
- Modeling Basis: Steady State of Mirror, Not Transient ; Use Average CTE Values
- Case A
  - ⇒ Initial Temperature: 293.15K
  - ⇒ Manifold Temperature: 77K
- Case B
  - ⇒ Initial Temp: 293.15K
  - ⇒ Manifold Temp: 4K

FEA Inputs

More Like Reality - Average CTE from 20-310K

- FEA Mesh
  - Elements:128044
  - Nodes: 192876
- Case A & B Model Inputs



Property	Symbol	Units	Solid Si	10% Si Foam	C/SiC	Bond Agent
Young's Modulus	E	GPa	130	1.3	250	12.7
Density	ρ	kg/m^3	2330	233	2650	7307
Poisson's Ratio	ν	-	0.24	0.24	0.17	0.45
Shear Modulus	G	GPa	52.4	0.52	106	4.4
CTE (average)	α	$1e^{-6}/K$	0.95	0.95	1.02	33
Conductivity	K	W/m-K	150	1.48	121	83.7
Specific Heat	C_p	J/kg-K	750	750	800	239

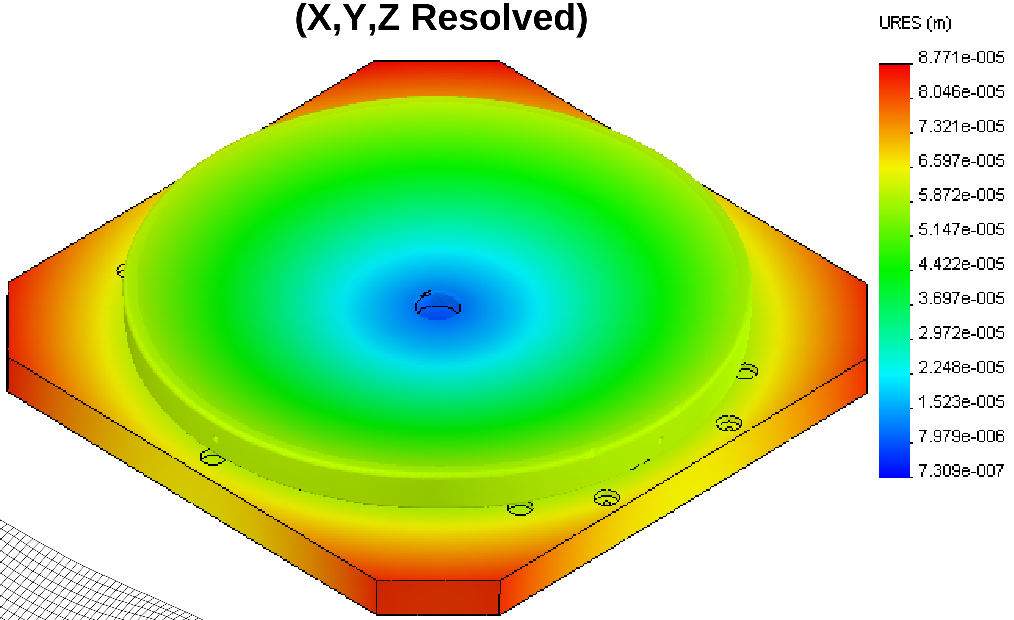
Case A Displacement Results

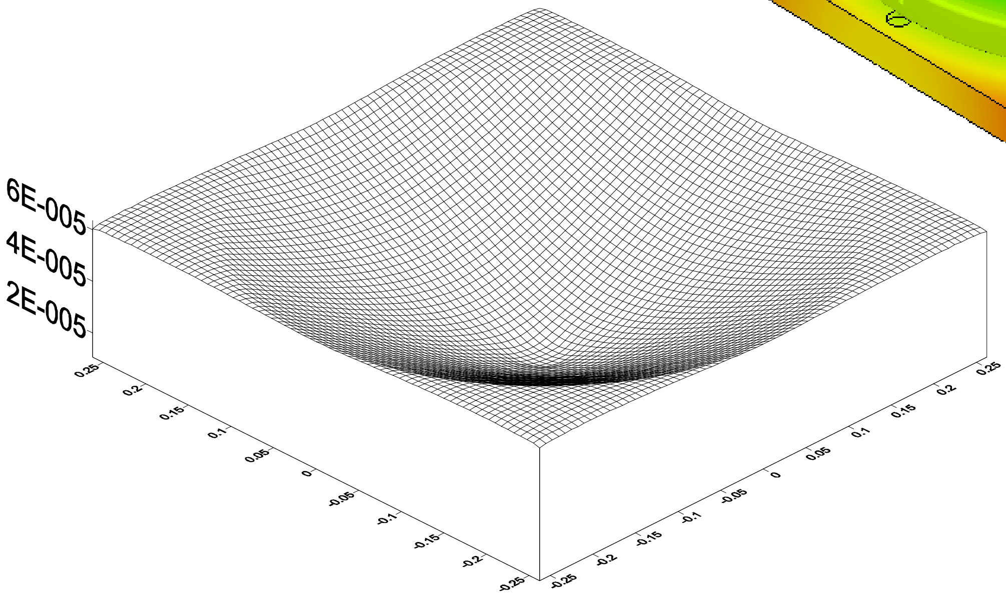
Initial Temp: 293.15K

Final Temp: 77K

Overall Assembly Displacement

(X,Y,Z Resolved)





Plot of face displacement

- Face Resolved Displacement (m) – Not Surface Error!
  - ⇒ Max: 6.08e-5
  - ⇒ Min: 1.10e-05
  - ⇒ RMS: 4.33e-05

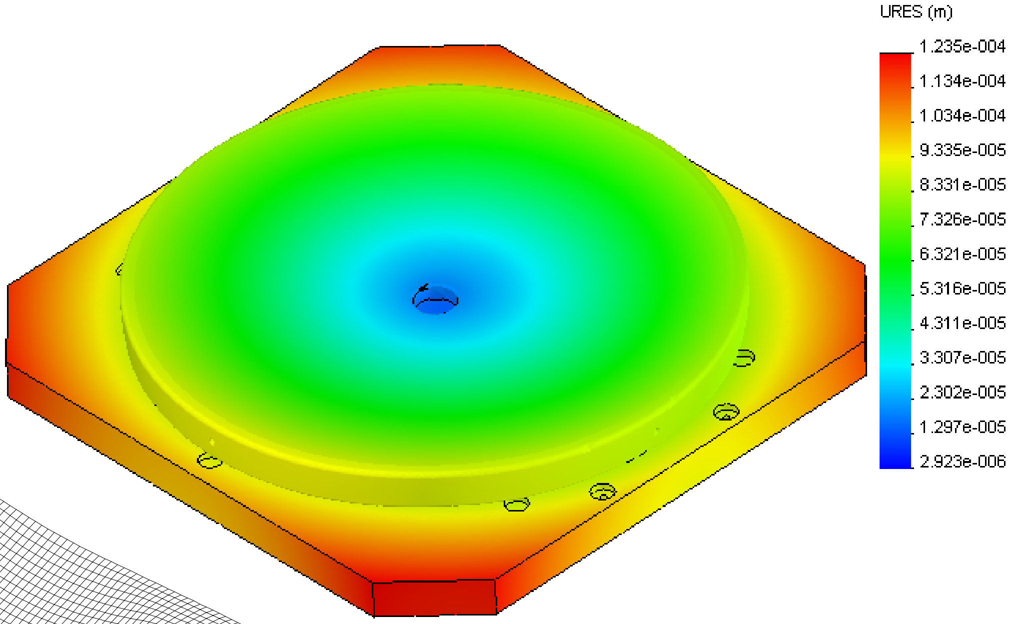
Case B Displacement Results

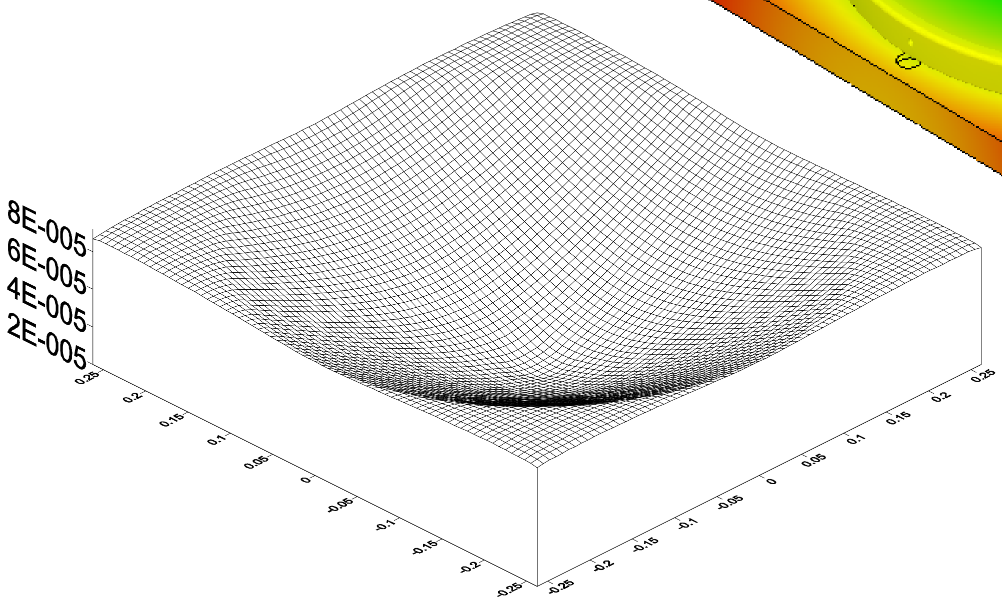
Initial Temp: 293.15K

Final Temp: 4K

Overall Assembly Displacement

(X,Y,Z Resolved)





Plot of face displacement

- Face Resolved Displacement (m) – Not Surface Error!
  - ⇒ Max: 8.95e-5
  - ⇒ Min: 2.03e-05
  - ⇒ RMS: 6.21e-05

Case B Shrinkage Data

Case B Detail

	Ux	Uy	Uz	Ures
max	7.72E-05	2.70E-06	8.04E-05	8.95E-05
min	-7.41E-05	-5.45E-05	-7.12E-05	2.03E-05
P-V	1.51E-04	5.72E-05	1.52E-04	6.92E-05
RMS	3.94E-05	2.82E-05	3.89E-05	6.21E-05

Shrinkage Dominates in Plane of Diameter

(Maximum Length Section Has Maximum ΔLength)

Surface Error Change is Proportional To Thickness of Mirror

P-V of 57 microns Over Physical Aperture Predicted By Model

Sanity Check at the Thickest Section of the Mirror:

0.041 m thick*0.95 μm/m/K*(293.15 -4 K) = 11.3 μm

Summary of Predictive Analysis

- FEM Mesh Is Too Coarse For Precise Analysis
- Best We Can Do is Order-of-Magnitude Prediction – Sanity Check Confirms
- What One Really, Really Wants Is:
  - ⇒ A Super Fine Mesh
  - ⇒ A Super Computer to Solve the Finite Difference Equations
  - ⇒ Transient Distortion Analysis with Time and Temperature Dependent Material Properties
  - ⇒ Real Time Dependent Chamber Temperature
  - ⇒ Heat Transfer Coefficients for Flowing Helium

Modeling Effort Gives ROM Distortions

MEASURED DATA IS REQUIRED TO ANCHOR AND REFINE MODEL